

Status of the Fourth Generation

A Brief Summary of B3SM-III Workshop in Four Parts

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Abstract

This summary of the 3rd “*Beyond the 3 Generation Standard Model*” workshop presents the following four statements (and their implications) for the ongoing and future searches of a fourth generation: 1) The enhancement of the Higgs gluon-gluon production cross-section times branching fraction for many of the search channels studied at the Large Hadron Collider (LHC) is not a flat factor of 9; 2) Electroweak precision data allows for not only a fourth generation, even more generations are allowed; 3) Consideration of mixing significantly changes the conclusions about the interpretation of experimental constraints, and even a fully-degenerate fourth generation becomes allowed; 4) The features that make a fourth generation of fermions attractive are still valid even under the light of initial LHC results.

Introduction

It is well known that the number of fundamental fermion families (generations) is not fixed within the Standard Model (SM). In recent years, with the discovery of neutrino oscillations, and reevaluations and reconsideration of electroweak (EW) precision data, it became evident that a fourth generation of fermions is not ruled out experimentally. Furthermore, such an extra generation was identified to have theoretically attractive features, and could help address some of the fundamental open questions of nature.

These arguments have been summarized briefly in [1], which is itself a summary of the first “*Beyond the 3-generation SM in the LHC era*” workshop held at CERN on 4-5 September 2008. Here we try to provide a brief summary of some of the key topics discussed in the third iteration of this thematic series, carrying the banner “*Third Workshop on Beyond 3 Generation Standard Model — Under the light of the initial LHC results*” (B3SM-III), which was held at Boğaziçi University in Istanbul on 23-25 October 2011. The full agenda and further details of the presentations can be found in [2].

Recent Tevatron and LHC results on the direct search of the fourth generation quarks, and indirect limits from perceived enhancement of $gg \rightarrow H$ cross-section, significantly reduce the allowed phase-space of chiral fourth generation theories. Therefore, more accurate formulations of the models and assumptions under which the limits are derived are needed to arrive at the final conclusion on the existence or absence of the fourth generation.

Enhancement of the Higgs discovery channels

Given that the gluon-gluon fusion process, i.e. the dominant production channel of the Higgs boson at the Large Hadron Collider (LHC), contains a quark loop, the addition of two new heavy quarks beyond the top quark would approximately triple the amplitude, and thus increase the production cross-section by a factor

of 9. This simple description is valid unless the Higgs boson is quite heavy ($m_H \gtrsim 2m_t$), in which case the contribution from the top to the production amplitude turns imaginary, and thus the enhancement of the amplitude-squared decreases to be around 5 ($2^2 + 1^2$ instead of 3^2). This behaviour is illustrated in [3] for a number of scenarios.

However, the quantity that is relevant to the Higgs searches at the LHC is not simply $\sigma(gg \rightarrow H)$, but the product $\kappa_X = \sigma(pp \rightarrow H) \times \mathcal{B}(H \rightarrow X\bar{X})$. This product can have an enhancement factor that is significantly lower than $5 \sim 9$ (even less than to 1 in some cases):

- The ZZ , WW , and¹ $\tau^+\tau^-$ final states: The Higgs boson can decay into the new fermions if they are lighter than half the Higgs mass. While this has relatively little effect for a very heavy Higgs boson, $\kappa_{W,Z,\tau}^{\text{SM4}}$ can be smaller than $\kappa_{W,Z,\tau}^{\text{SM3}}$ if the mass of the fourth generation neutral lepton is close to the current experimental bounds² ($50 \sim 60$ GeV) and the Higgs boson is light ($m_H \lesssim 150$ GeV) [5, 6].
- The $\gamma\gamma$ final state: Unlike the gluon-gluon fusion process, the loop diagram contains not only heavy fermions (including the heavy charged lepton), but also the weak boson as well, and destructive interference cancels out most of the enhancement in production, leading to $\kappa_\gamma^{\text{SM4}} \approx \kappa_\gamma^{\text{SM3}}$.

Therefore, care needs to be taken in the interpretation of the recent ATLAS and CMS results on the Higgs search [7]. Certainly, a conclusion like “the idea of a sequential fourth generation of quarks and leptons is in serious trouble” [8] is quite premature. Non-observation of the enhanced $gg \rightarrow H$ signal may as well be the signature of the Higgs absence (or its very high mass as in warped [9] and other scenarios), rather than the signature of the absence of the fourth generation. Final conclusion should be reserved for an update with higher luminosity. Moreover, the results from the search for the Higgs will not be fully conclusive unless they are complemented with direct searches for the fourth-family fermions themselves, as the presence of a light neutral lepton or an extended scalar sector (as in [10]) can still resolve the tension between a sequential fourth generation and measurements of a SM-like Higgs. Finally, in the case of a vector-like new generation,³ where the quarks have mass terms that do not originate from EW symmetry breaking (such as the model presented in [12]), there is no enhancement of $gg \rightarrow H$ production, and the Higgs constraints would be very different.

Generations beyond the Fourth

Since the fourth generation was itself incorrectly considered to be inconsistent with the EW precision data, generations beyond the fourth were considered to be outright impossible. However, as the fourth generation was shown to have sufficiently wide allowed parameter space, possibilities of considering more generations have recently been revisited. In [13], a fit to the EW data using the LEPTOP code [14] for the example scenario of $m_{t'} = m_{b'} = 300$ GeV, $m_{\tau'} = 200$ GeV,⁴ showed that, while unfavored, two extra generations with Dirac-type neutrinos had not been ruled out yet. Analysis of the Peskin-Takeuchi oblique parameters S , T using the OPUCEM code [15] confirms this finding, even for $m_{t'} = m_{b'} = 500$ GeV or higher. Furthermore, it is found that if the neutrinos of the extra generations are of Majorana nature, it is possible to accommodate even more than 5 generations with S , T values within 1σ of the LEP EWWG measurements [16].

If a SM-like Higgs boson is assumed to exist, the current absence of any Higgs signal from the LHC obviously undermines the possibility of quarks from extra generations.⁵ Therefore the fact that such extra generations are not excluded by the EW data could be interpreted as a pointer to extending only the lepton sector in a SM-like Higgs scenario. It is worth noting that there is theoretical motivation for such extra generations. For example, in [18], it is shown that with 5 generations and two right-handed neutrinos it might be possible to generate all present data on the observed light neutrino mass hierarchy.

¹ In the $H \rightarrow \tau^+\tau^-$ analysis channel, the selection criteria often preferentially keep events produced through the vector boson fusion process, so effective enhancement would be even smaller than what is discussed here.

² Exact limit extracted from just the Z-lineshape is $m_{\nu_\tau} > 46.7$ GeV at 95% CL [4].

³ New vector-like quarks might offer a number of attractive properties. For an overview, see [11].

⁴ We use the notation of [1], with primed symbols for third-generation fermions representing their fourth generation counterparts.

⁵ In the case of infinitely heavy new fermions, the enhancement factor for the production of a 120 GeV Higgs boson via gluon-gluon fusion is 8.5, 24 and 47 in SM with four, five and six generations respectively [17].

Consequences of Flavor Mixings

Implications of dropping the unitarity requirement from the 3×3 PMNS matrix were pointed out in [19]. Precision of the measured values of the Fermi constant G_F and CKM parameter $|V_{ud}|$ are significantly reduced. The 2σ range for the 4×4 PMNS parameter U_{e4} is $0.021 < |U_{e4}| < 0.089$, and the p-value for $|U_{e4}| = 0$ (as would be expected in SM with 3 generations) is only 2.6%. Such large mixings has itself some interesting implications: in the absence of any other physics, experimental constraints from neutrinoless double beta decay would imply Dirac or pseudo-Dirac (nearly degenerate mass eigenstates obtained when the Majorana mass is much smaller than the Dirac mass) nature⁶ for the fourth generation neutrinos [21].

In the quark sector, the importance of considering quark mixings has recently been discussed in [22]. As the quark mixings increase the T parameter without changing the S parameter, it becomes possible to accommodate even a fully-degenerate fourth family, contrary to the widely quoted sentiment in [23].⁷

In light of all these findings, it is clear that a fully consistent picture cannot be drawn unless the flavor and EW data are considered together. Furthermore, a consequence of considering fermion mixings is that new physics may not enter only through gauge boson self-energies, therefore considerations of only the oblique parameters are not enough [25], and a new generic approach for computing the EW corrections is being developed to be included in the global fitter program, CKM4FITTER [26].

Preliminary results from the first global fit using the CKM4FITTER indicate that the currently available data favors values around 0.1-0.2 for the 4×4 CKM parameters $|V_{cb'}|$ and $|V_{tb'}|$ [26].⁸ This finding has important consequences for the direct searches at the LHC, as the currently most stringent mass constraints on the fourth-generation quarks assume either $\mathcal{B}(t' \rightarrow Wb) = 100\%$ or $\mathcal{B}(b' \rightarrow Wt) = 100\%$ [28, 29]. An independent (but simpler) analysis by the OPUCEM code yields very similar results for the mixings as those of the CKM4FITTER, and also indicate a tendency for decreasing $\mathcal{B} \sim |V_{tb'}|^2 / (|V_{tb'}|^2 + |V_{cb'}|^2)$ as the quark masses increase [30].

Finally, irrespective of what is inferred from the EW and CKM data, it is clear that the mass limits obtained from direct searches for new quarks and leptons should always be given as a function of the mixing angles. In particular in the case of the small mixing angles of the fourth generation quarks with the other generations the detection efficiency can be reduced due to displaced vertices or quasi-stable fourth generation hadrons. This will require specialized search strategy and interpretations.

Fourth Generation, Open Questions and New Models

In [1], it was highlighted that a fourth generation could address or provide clues about a number of open problems (baryon asymmetry of the universe, Higgs naturalness, fermion mass hierarchy, dark matter). Most of these arguments were reviewed in this workshop and found to be still valid and interesting in the light of the recent LHC data [31]. Amongst these, the topic that received the most attention was the role that the fourth generation quarks could play in EW symmetry breaking through some strong dynamics,⁹ since direct searches have pushed the quark mass lower limits close to 500 GeV [28], not far from the so-called unitary bound.

Surprisingly, little is known about a strong Yukawa theory. Different groups have recently been exploring different aspects of the strong regime through various approaches. For example, following the second B3SM workshop in January 2010 [33], a collaboration was formed to study the Higgs-Yukawa theory on the lattice in the regime of large bare Yukawa coupling; their recent progress is summarized in [34]. Schwinger-Dyson approach is taken in [35], which allows the computation of the self-energy of the fourth generation fermions and subsequently their condensates; the results obtained are consistent with the interpretation of the perturbative evolution of the Yukawa couplings [36]. Estimates for the phenomenology of Yukawa-bound $Q\bar{Q}$ states are made in [37], using a relativistic Bethe-Salpeter equation approach to motivate the Yukawa binding energy before the unitarity bound sets in. This work also concludes that the current

⁶ Further constraints (which apply not only to fourth generation) have recently been extracted on the grounds that lepton number violation due to the interactions involving new Majorana neutrinos can wash out considerably any GUT scale generated or otherwise preexisting baryon asymmetry of the universe [20].

⁷ Almost degenerate fourth family quarks and charged lepton are predicted by the Flavor Democracy Hypothesis (see [24] and references therein.)

⁸ These large values seem to contradict those found in [27], probably because of not yet considering $Z \rightarrow b\bar{b}$ constraint.

⁹ Dynamical EW symmetry breaking without the presence of some strong dynamics has been most recently considered in [32], but the recent experimental results seem to exclude such a scenario.

search for pair-produced fourth generation quarks can continue beyond the unitarity bound, as the leading $gg \rightarrow Q\bar{Q}$ fusion is found to not exhibit significant resonance phenomena.

A fourth generation is an attractive tool for model building. The explanations it can provide for some of the open questions of physics is applicable irrespective of whether there is beyond the SM (BSM) physics or not. Many of its indirect consequences, such as the enhancements in neutron EDM [38], μ -e conversions [39], $B_s \rightarrow \mu\mu$ branching fraction [40], etc., have also been computed and found to be within current experimental bounds, while $B_s \rightarrow \mu\mu$ and mixing-dependent CPV in $B_s \rightarrow J/\psi\phi$ might still exhibit indications for the fourth generation [40], despite the recent “setback” from LHCb [41]. A number of models combine fourth generation with BSM ideas to address further experimental hints from the colliders. For example, a new phenomenological model involving strongly coupled fourth generation quarks has been proposed in [42] to address top-pair forward-backward asymmetry observed at the Tevatron experiments [43]. It is interesting to note that the experimental signatures of the fourth generation in new models can be quite unusual and might require significant rethinking of conventional searches at the LHC [24, 44].

Conclusion

“The rumors of my death have been greatly exaggerated, again!” - Fourth Generation

We are approaching very fast the moment when the LHC searches will discover the fourth generation or exclude it in the TeV mass scales. The latter requires careful searches in multiple channels and full phase space of masses and mixing angles. From an experimental point of view, these searches are needed irrespective of the indirect constraints, which have been misinterpreted multiple times in the past. If no sign of the fourth generation is found at the LHC, the firm experimental proof of only 3 generations would be the fundamental result which will require satisfactory theoretical explanation beyond the Standard Model.

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